Recent Results from STAR at RHIC

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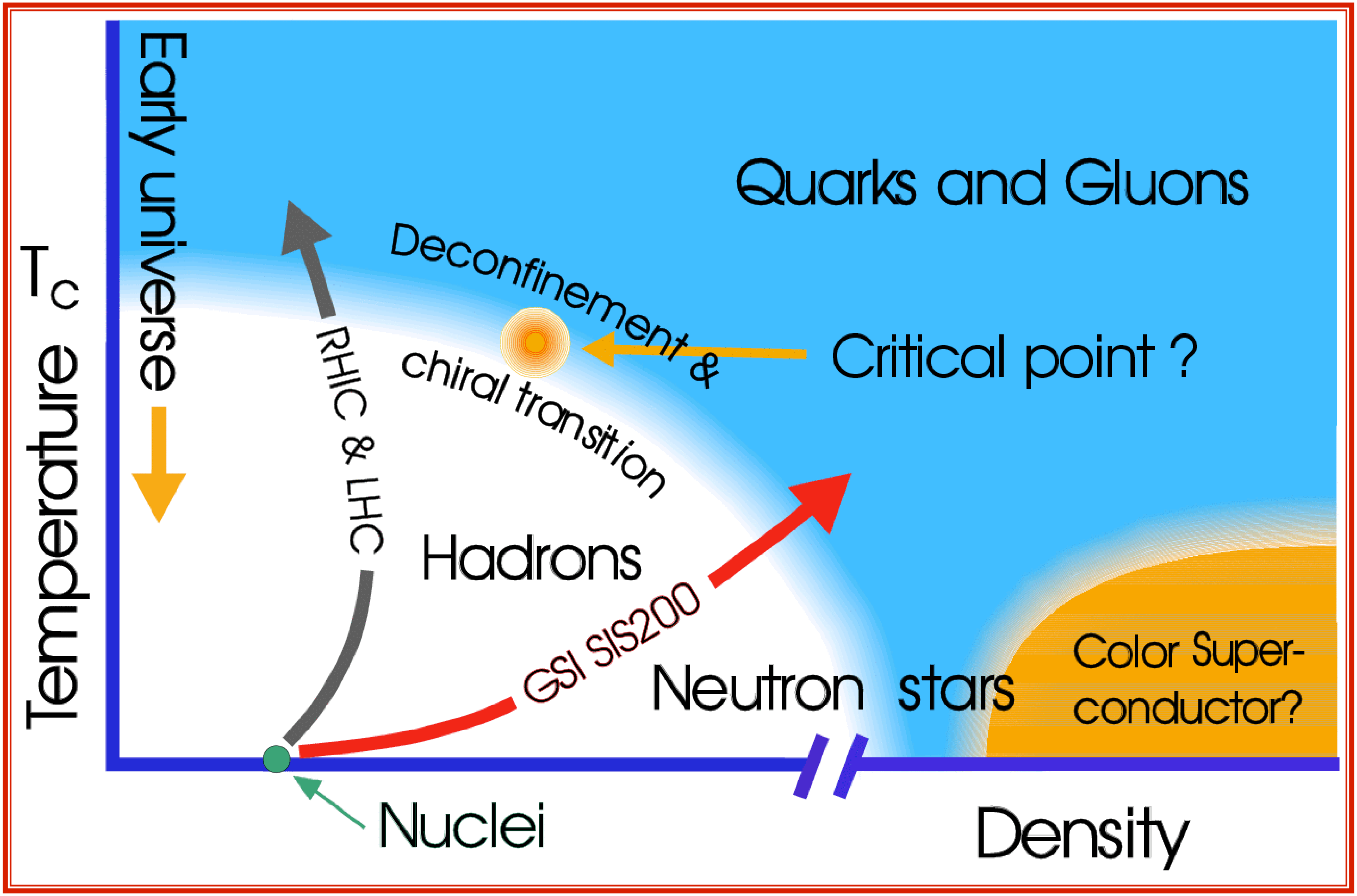
Outline

- Introduction
- Energy loss - QCD at work
- Charm production
- Bulk properties - ∂P_{QCD}
- Summary and Outlook

Other STAR Physics Topics

1) Correlation and fluctuation
2) Ultra-peripheral Collision
3) Resonance
4) Spin
5) Pentaquark search

http://www.star.bnl.gov/STAR/


Quarks and Gluons
Deconfinement &
Critical point ?
chiral transition
RHIC & LHC
Early universe
Temperature
T_C
Hadrons
GSI SIS200
Neutron stars
Color Super-
conductor?
Nuclei
Density

Study of Nuclear Collisions Like…

P.C. Sereno *et al*. **Science**, Nov. 13, 1298(1998).

(Spinosaurid)

Physics Goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

- direct photons, leptons
- "jets" and heavy flavor
- correlations

Bulk probes

- spectra, v_1, v_2 …
- partonic collectivity
- fluctuations

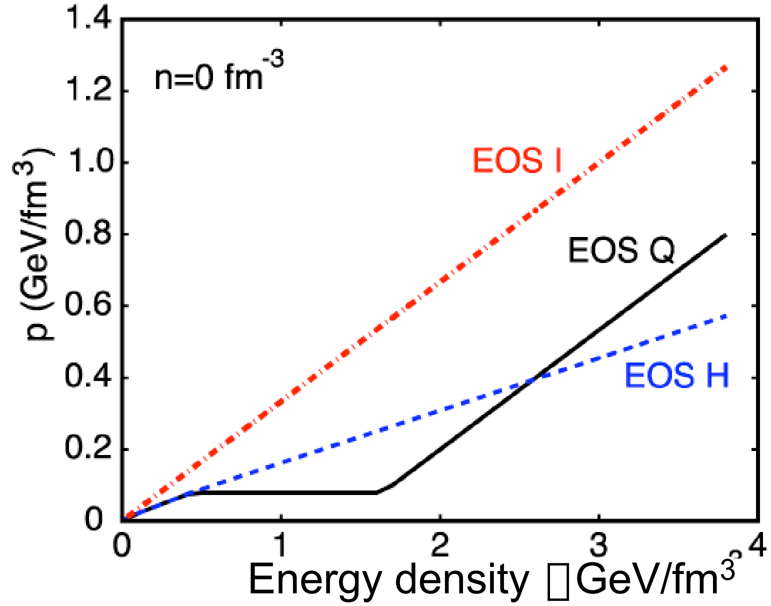
Hydrodynamic Flow = Collectivity Local Thermalization

Equation of State

$$\partial_\mu T^{\mu\nu} = 0$$

$$\partial_\mu j^\mu = 0 \qquad j^\mu(x) = n(x)u^\mu(x)$$

$$T^{\mu\nu} = [\varepsilon(x) + p(x)]u^\mu u^\nu - g^{\mu\nu} p(x)$$



With given degrees of freedom, the EOS - the system response to the changes of the thermal condition - is fixed by its ***p*** and ***T*** (or ε).

Equation of state:

- **EOS I** : relativistic ideal gas: $p = \varepsilon/3$
- **EOS H**: resonance gas: $p \sim \varepsilon/6$
- **EOS Q**: Maxwell construction:
  T_{crit}= 165 MeV, $B^{1/4}$ = 0.23 GeV
  ε_{lat}=1.15 GeV/fm^3

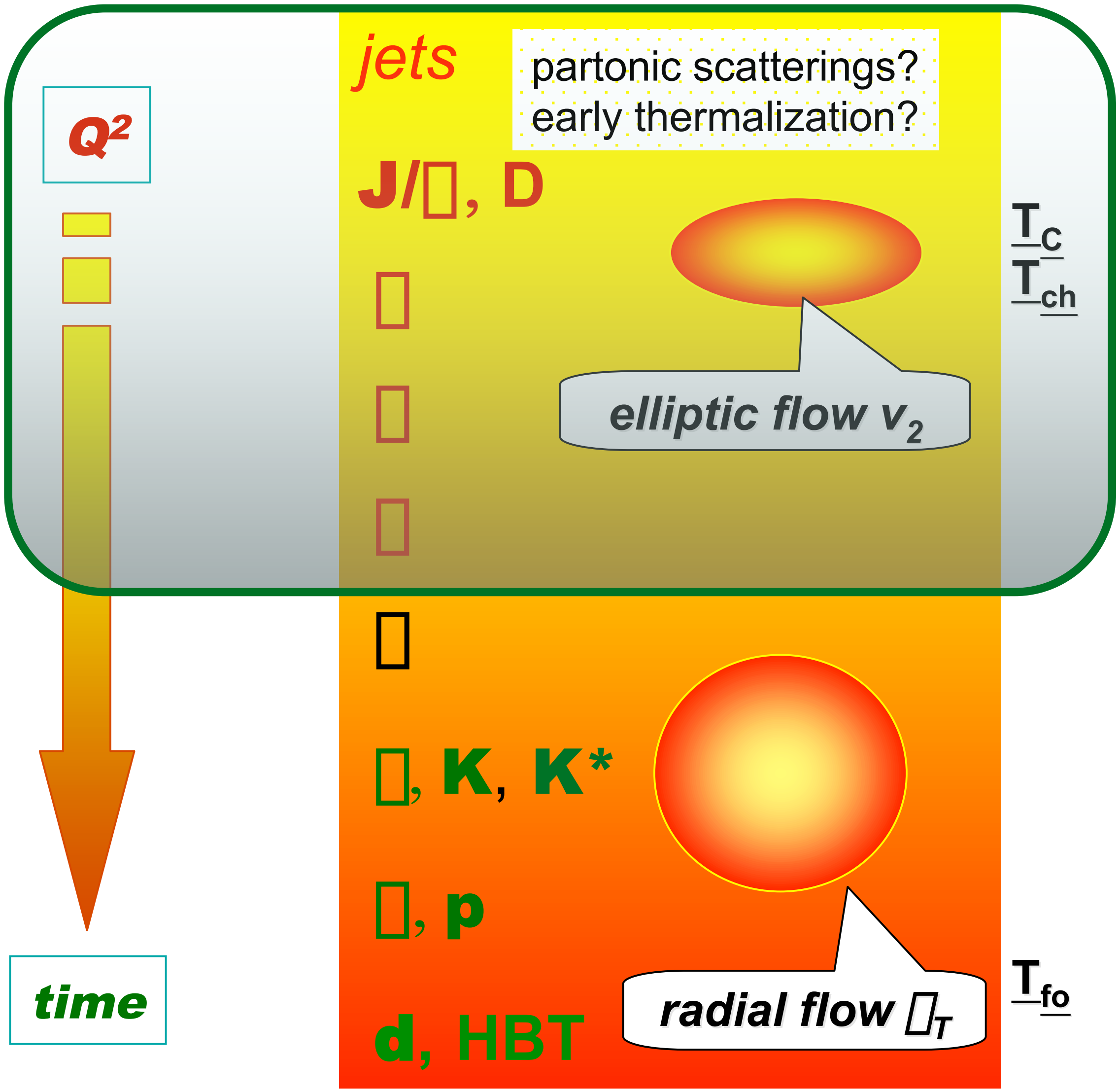
P. Kolb et al., Phys. Rev. ***C62****, 054909 (2000).*

High-energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

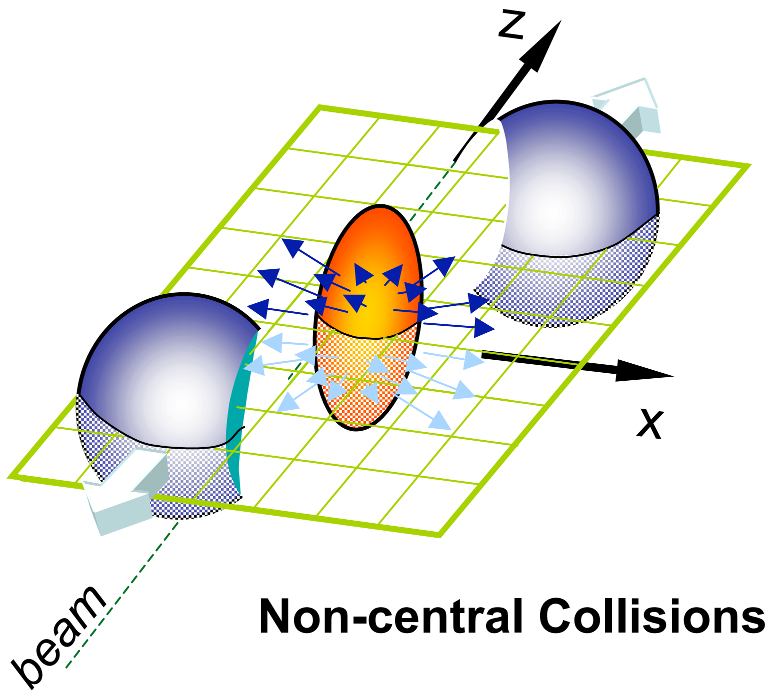
System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop

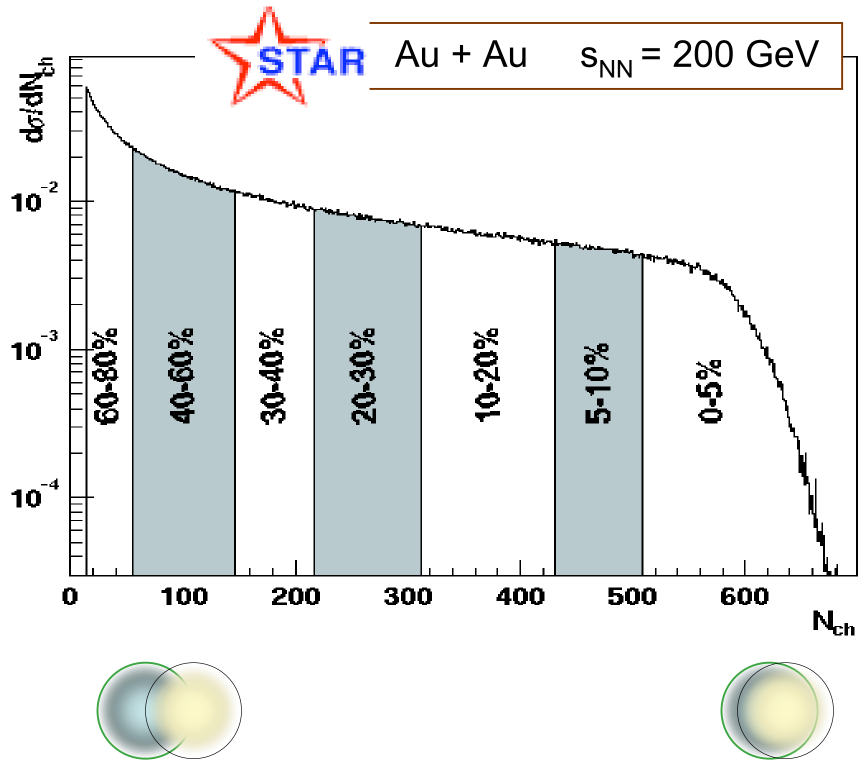


Collision Geometry

//Talk/2004/11MIT/nxu_mit_26oct04//

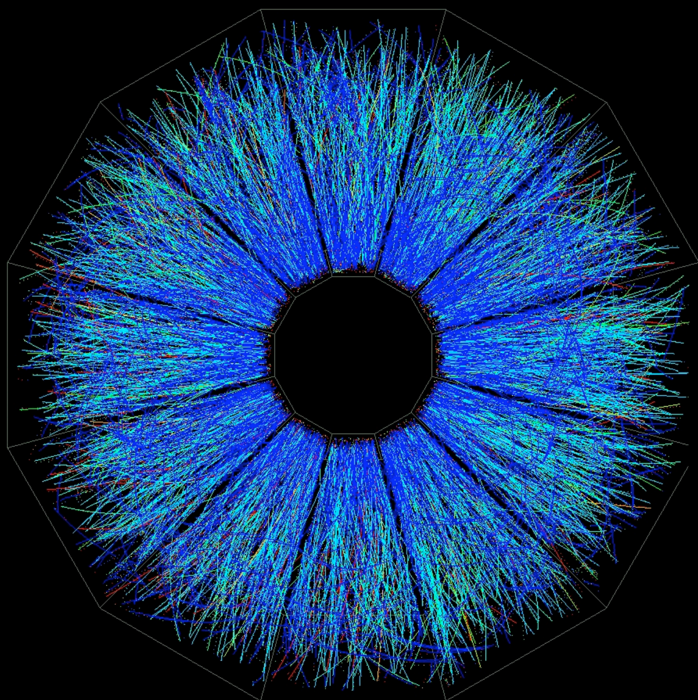


Non-central Collisions

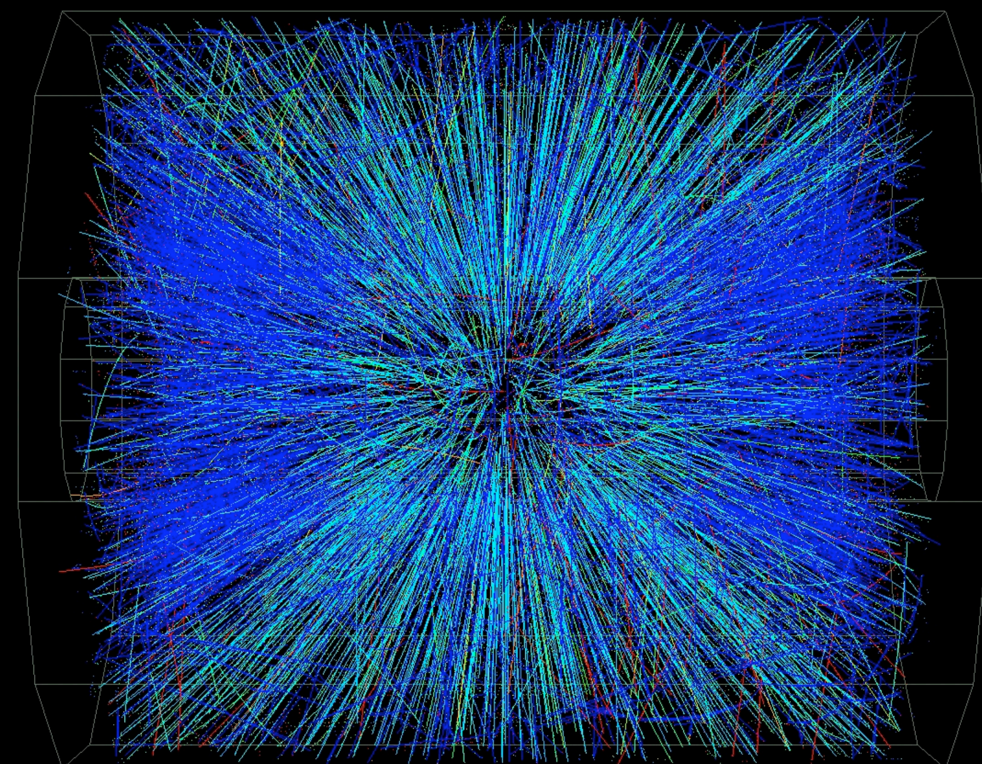


Number of participants: number of incoming nucleons in the overlap region
Number of binary collisions: number of inelastic nucleon-nucleon collisions
Charged particle multiplicity ⎕ collision centrality
Reaction plane: x-z plane

Au + Au Collisions at RHIC



Central Event



STAR

(real-time Level 3)

STAR: TPC & MRPC-TOF

//Talk/2004/11MIT/nxu_mit_26oct04//

A new technology - Multi-gap Resistive Plate Chamber (MRPC), adopted from CERN-Alice

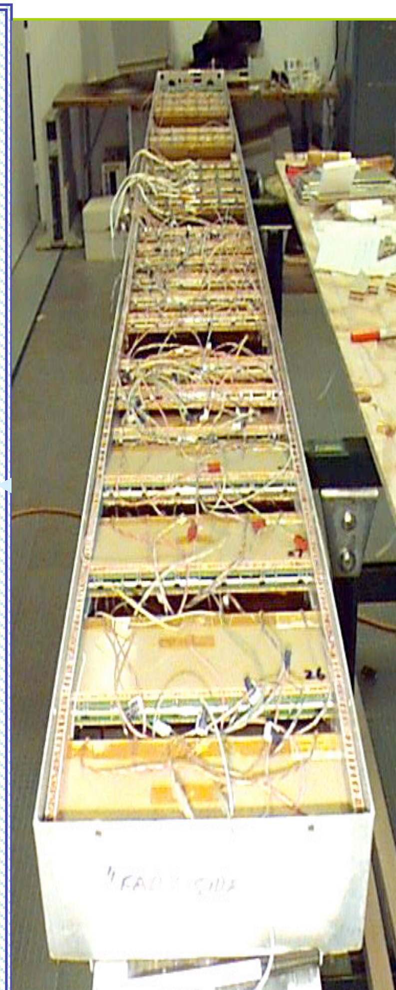
- A prototype detector of time-of-flight (**TOFr**) was installed in Run3
- One tray: ~ 0.3% of TPC coverage
- Intrinsic timing resolution: ~ 85 ps

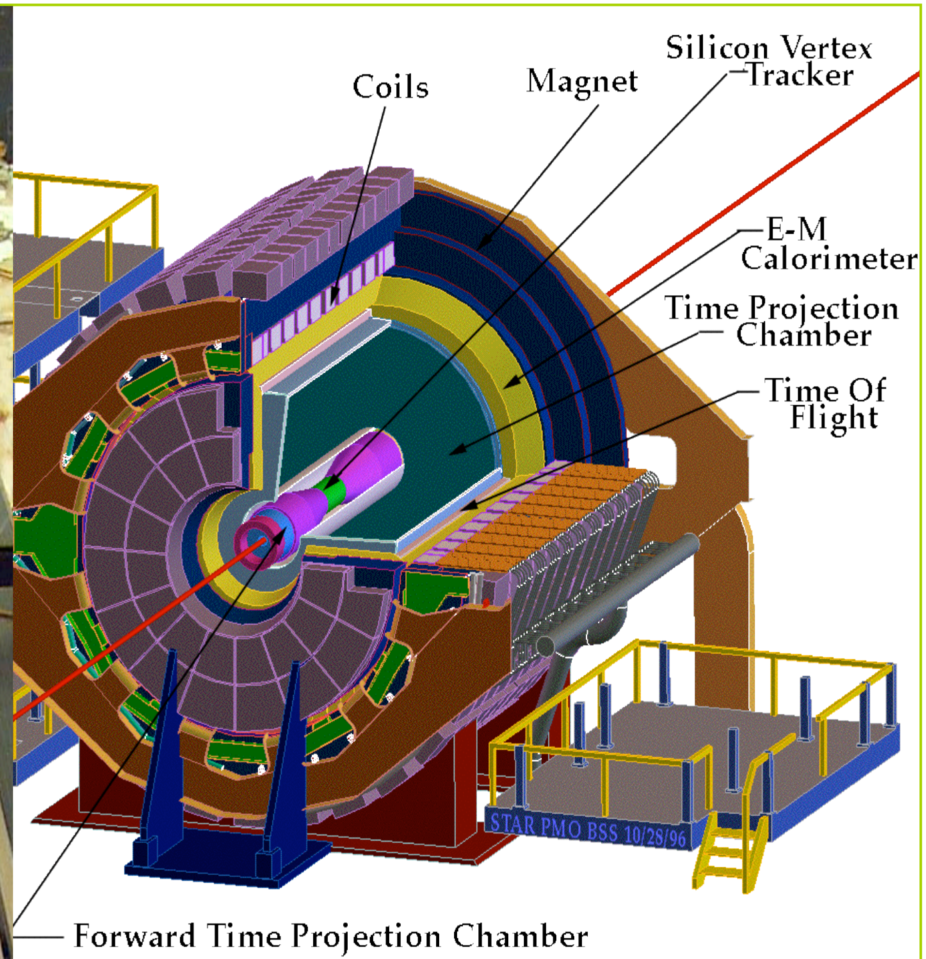
pion/kaon ID:

p_T ~ 1.7 GeV/c

proton ID:

p_T ~ 3 GeV/c





TPC dE/dx PID:
pion/kaon: p_T ~ 0.6 GeV/c; proton p_T ~ 1.2 GeV/c

STAR TOFr PID

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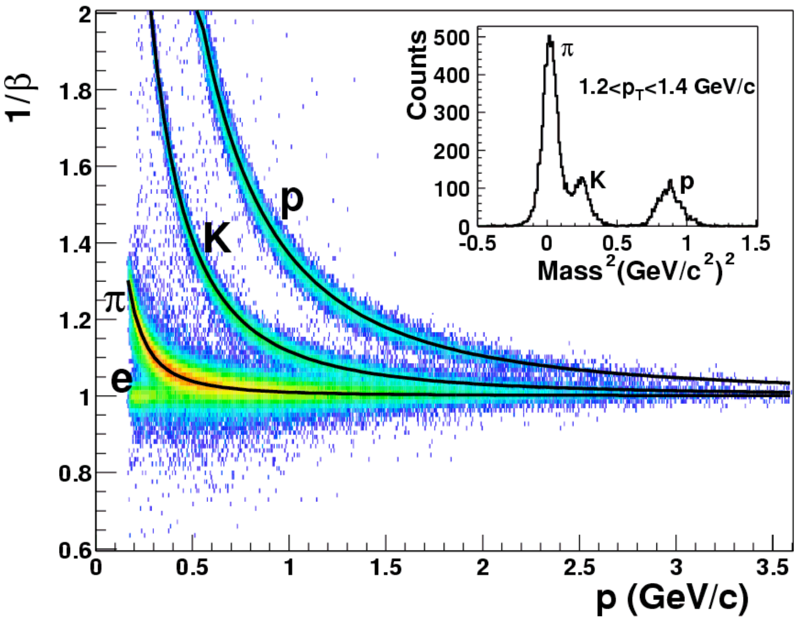
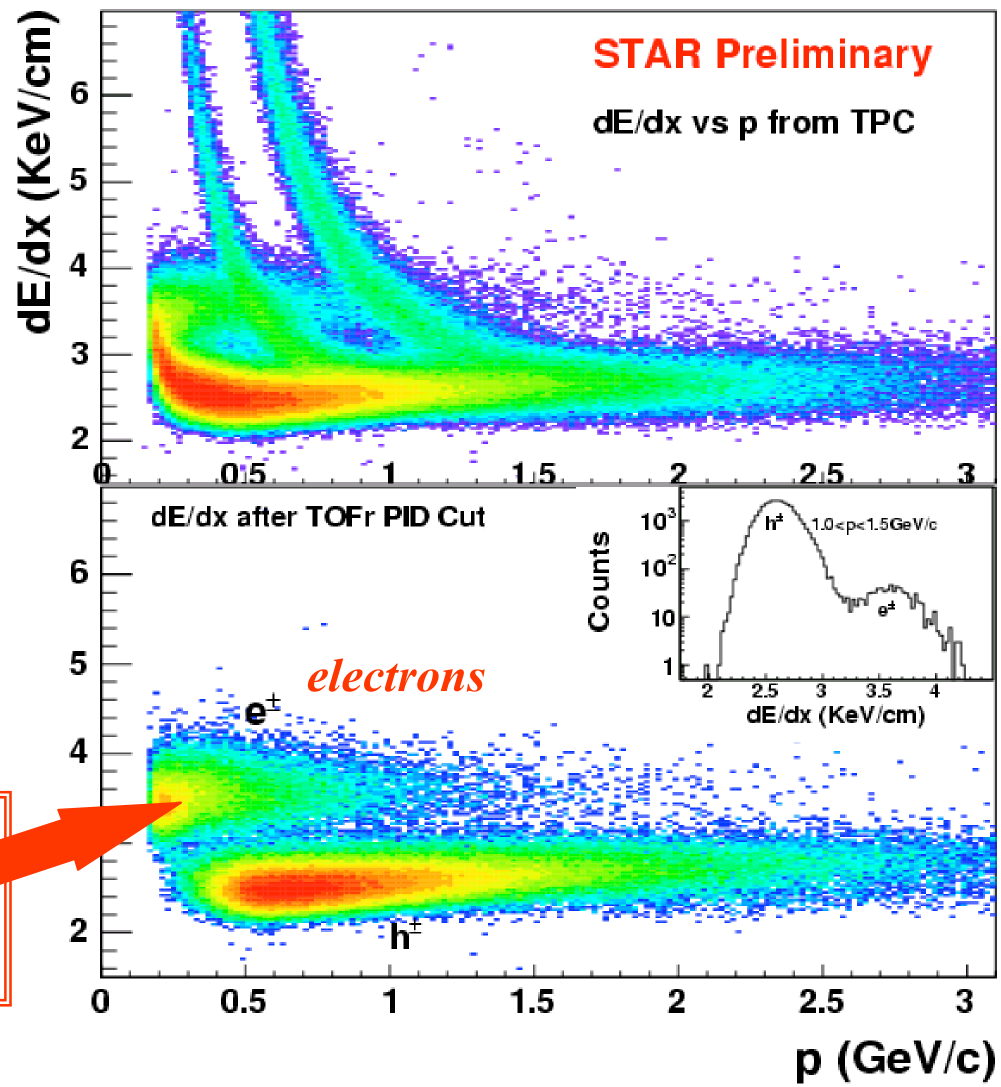


Hadron identification:
STAR Collaboration, *nucl-ex/0309012*

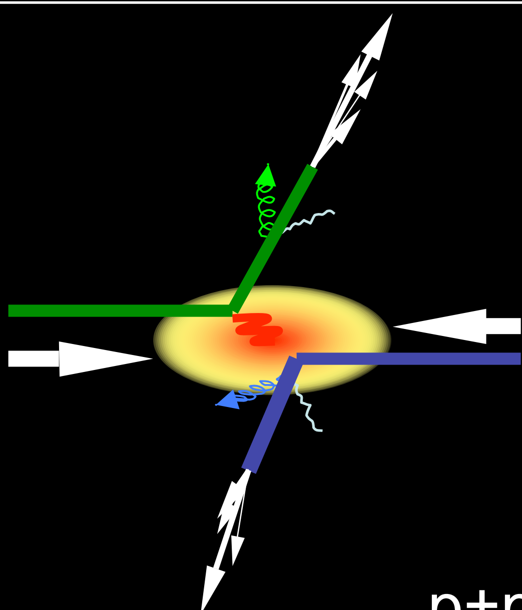


Electron identification:

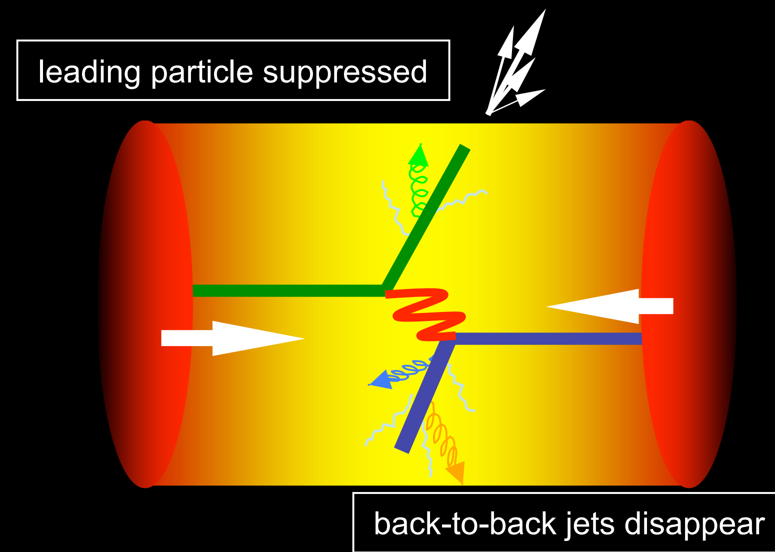
TOFr |1/ß-1| < 0.03

TPC dE/dx electrons!!!

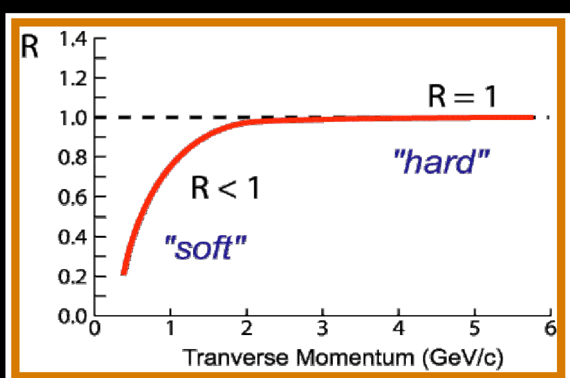
Energy Loss in A+A Collisions



p+p



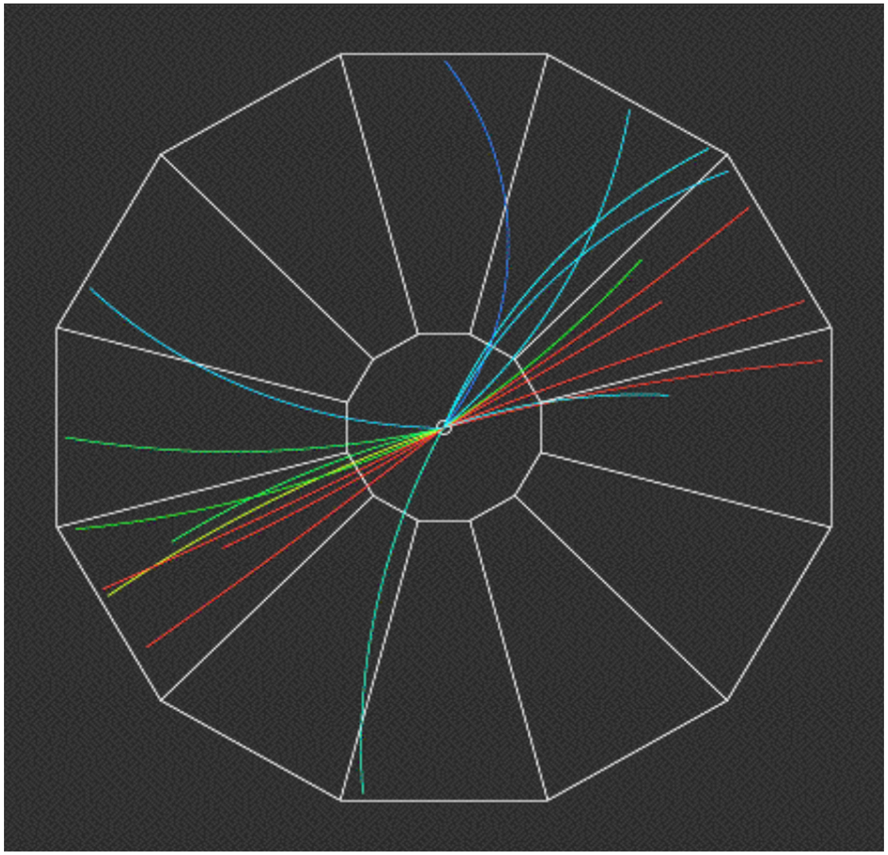
Au + Au

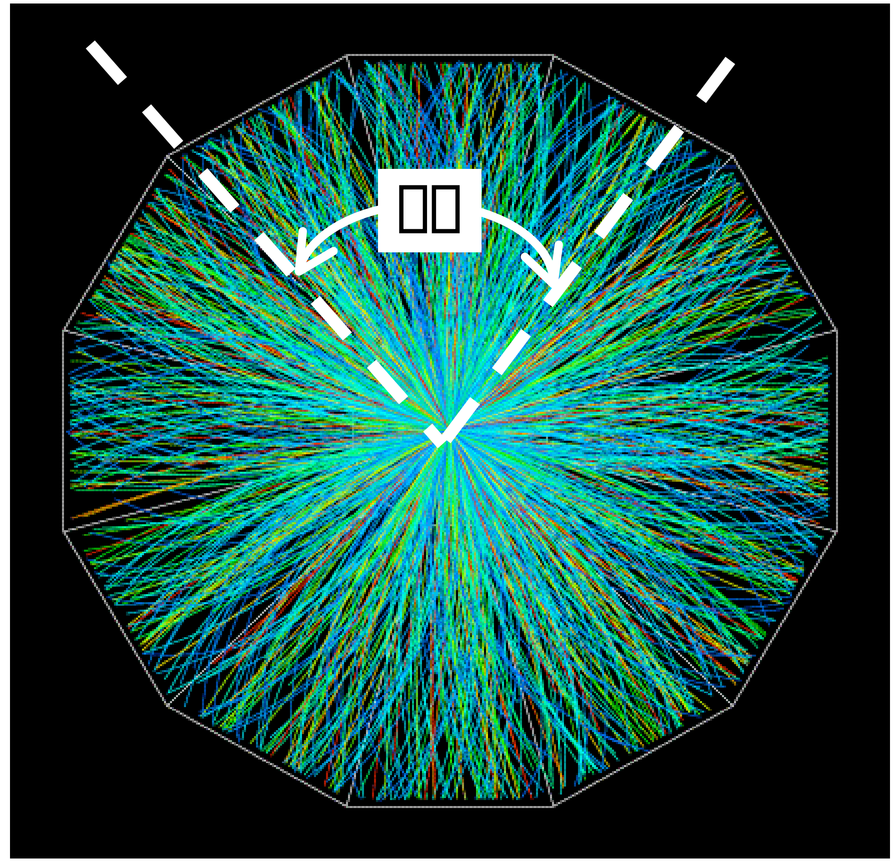


Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

‘Jets’ Observation at RHIC

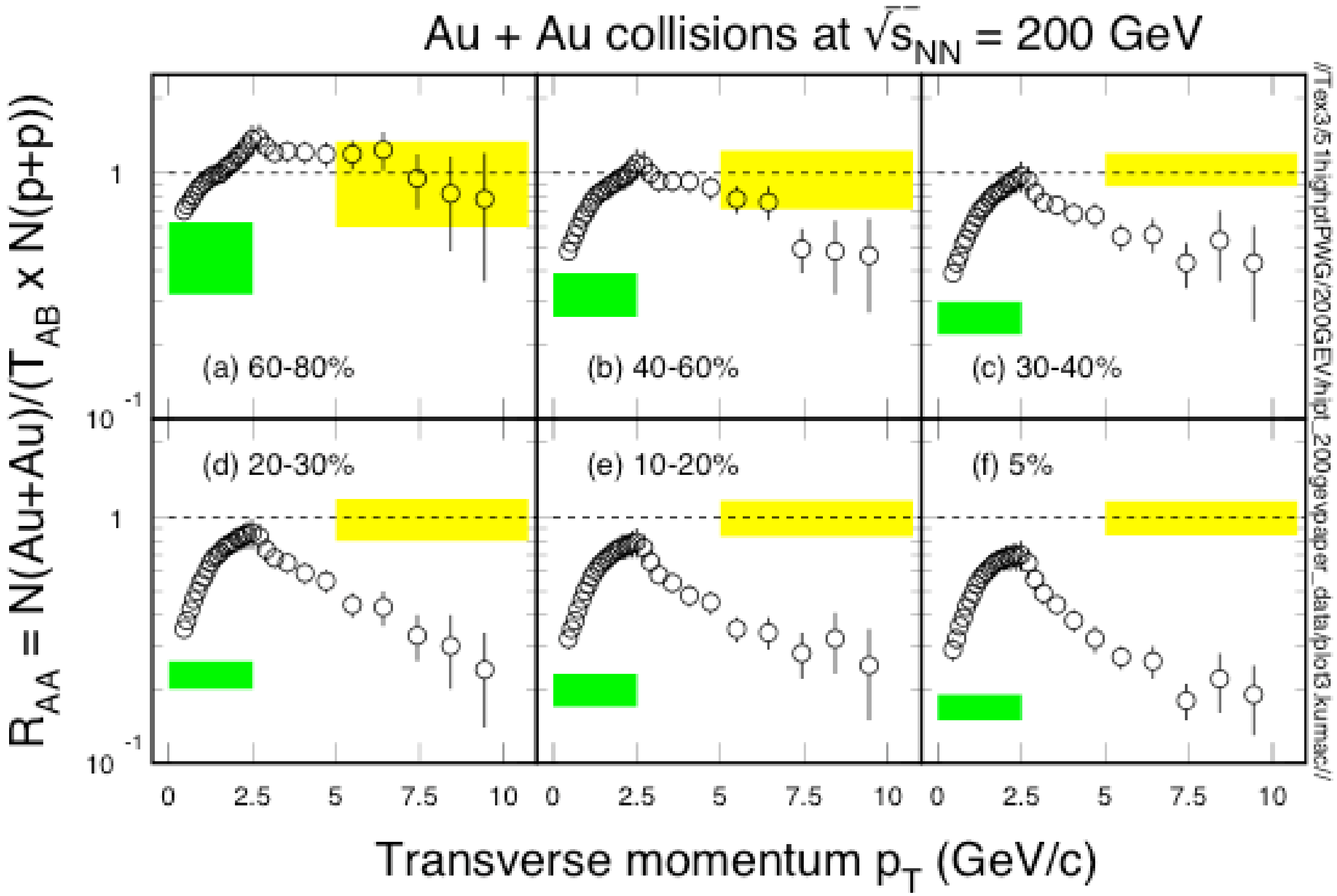


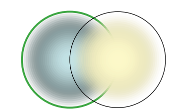


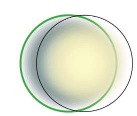
p+p collisions at RHIC
Jet like events observed

Au+Au collisions at RHIC
Jets effects?

Hadron Suppression at RHIC







Hadron suppression in more central Au+Au collisions!

Suppression and Correlation

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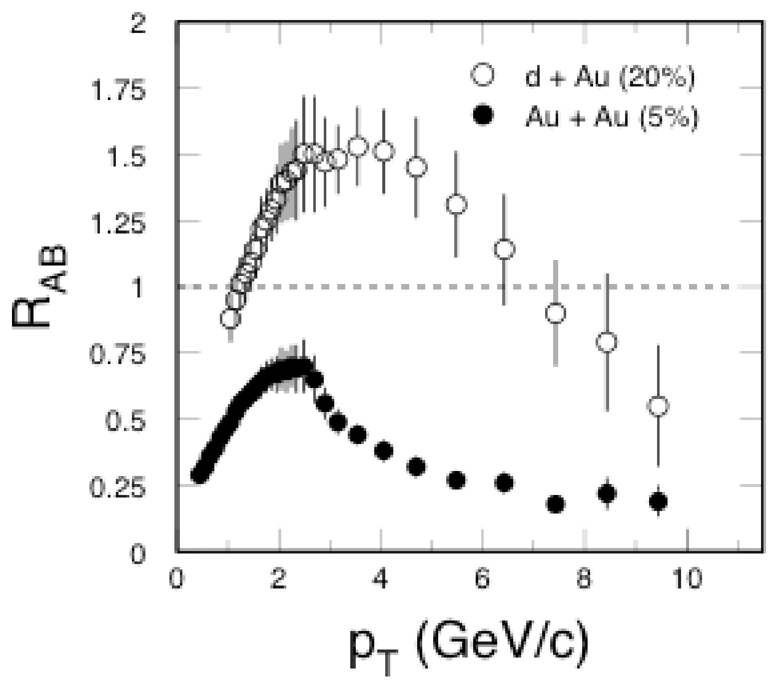

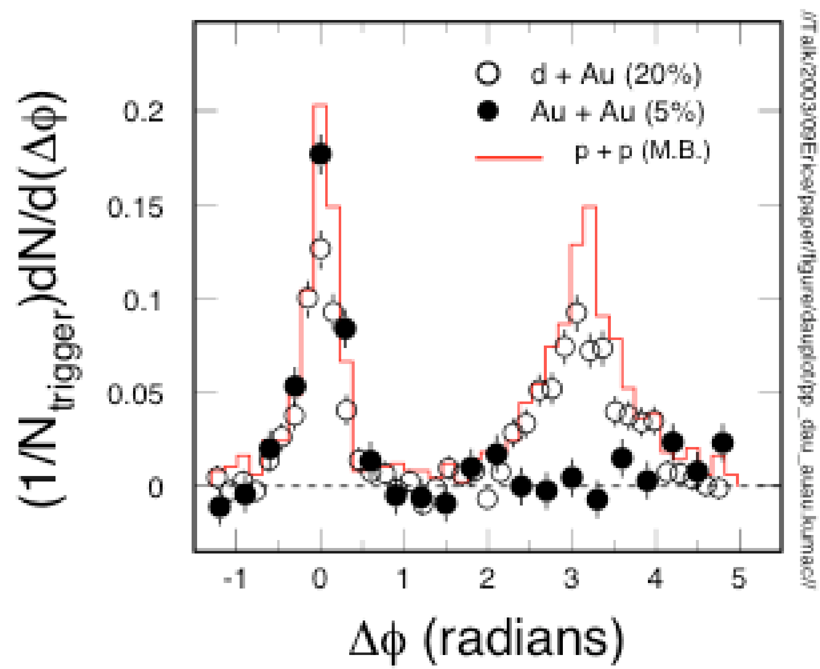

In central Au+Au collisions: hadrons are suppressed and back-to-back 'jets' are disappeared. Different from p+p and d+Au collisions.

Energy density at RHIC: ϵ > 5 GeV/fm^3 ~ 30ϵ_0

Parton energy loss:	Bjorken	1982
("**Jet quenching**")	Gyulassy & Wang	1992

…

Azimuthal Angle Dependence

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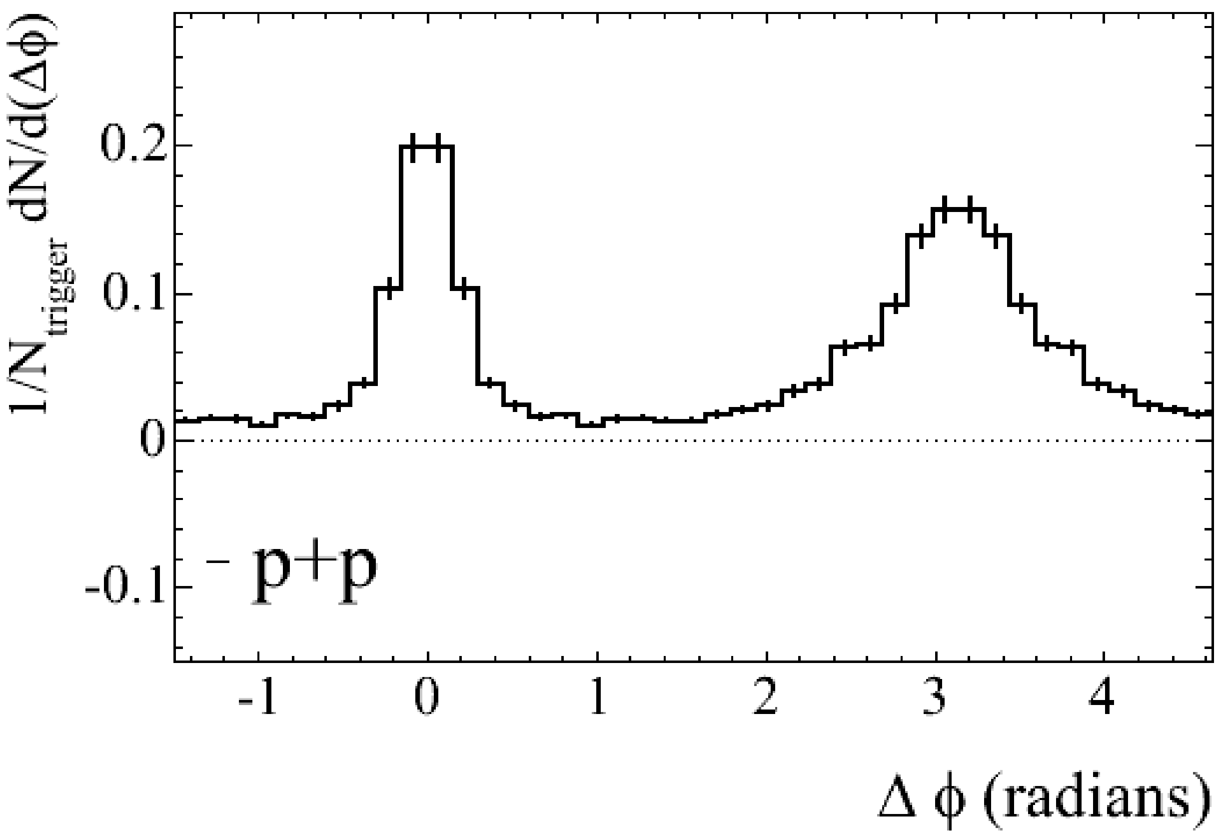
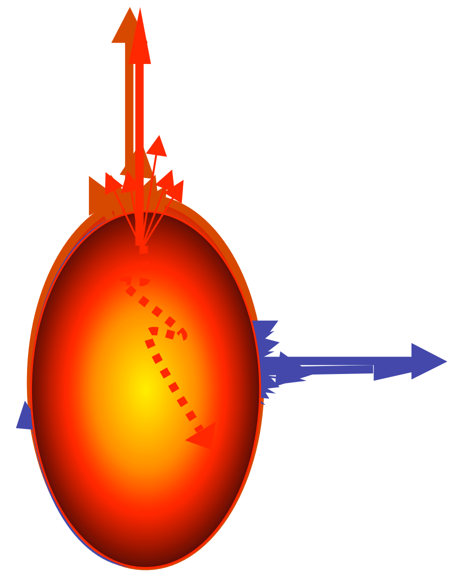
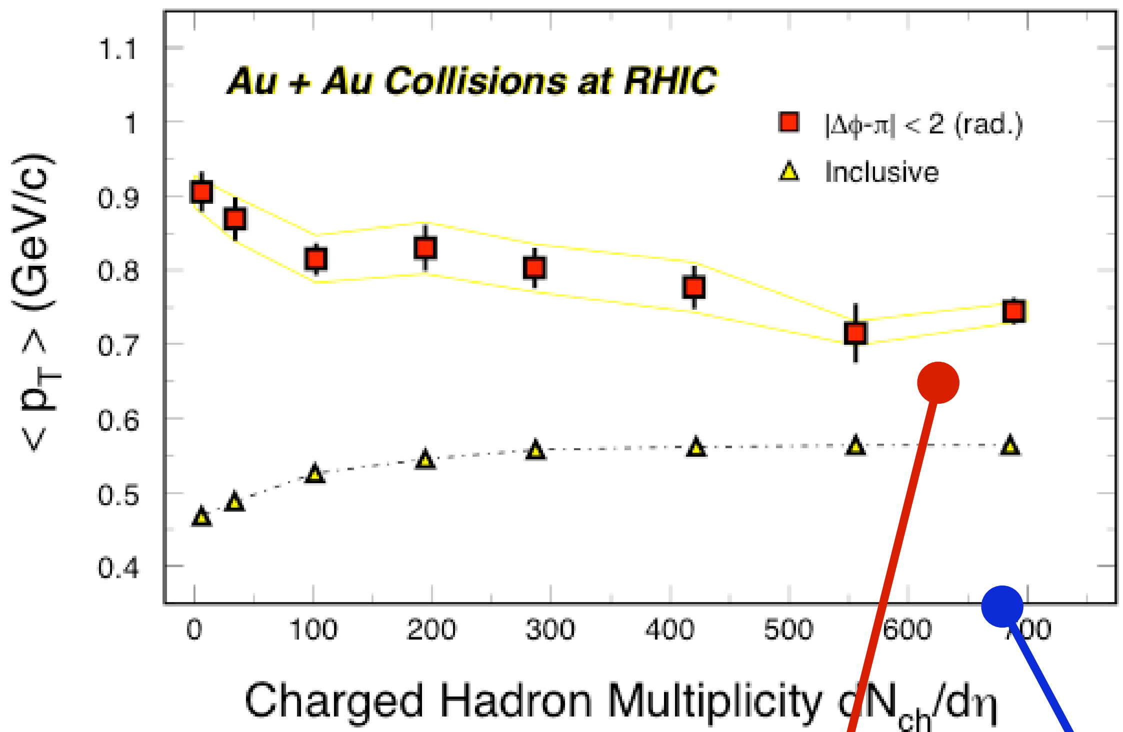
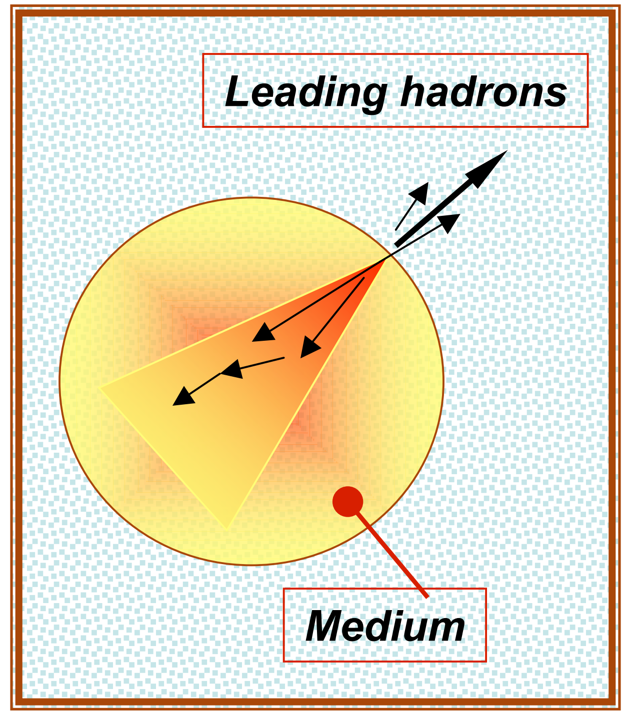




- Away-side suppression: larger for out-of-plane than in-plane!
- The energy loss depends on the distance traveled through the medium!
- Geometry of the dense medium imprints itself on correlations**!**

Energy Loss and Equilibrium





In Au +Au collision at RHIC:

- Suppression at the intermediate p_T region - energy loss

- The energy loss leads to progressive equilibrium in Au+Au collisions

STAR: nucl-ex/0404010

Energy Loss

(1) Measured spectra show evidence of suppression
up to $p_T \sim 6$ GeV/c;

(2) Jet-like behavior observed in correlations:
- hard scatterings in AA collisions
- disappearance of back-to-back correlations
- length dependence

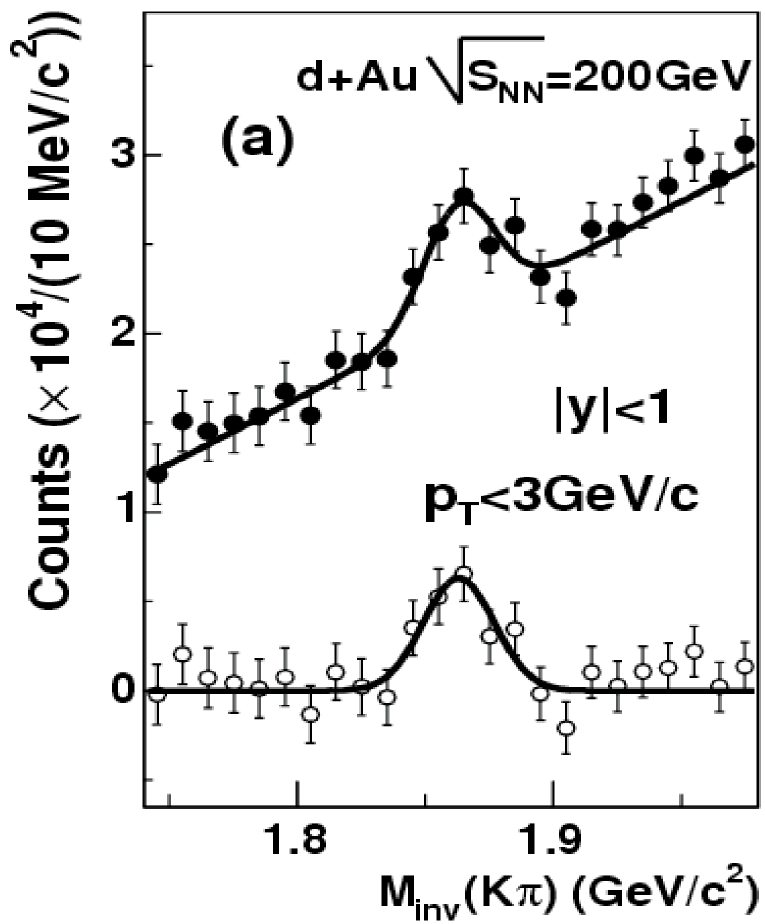
⇨ ***"Partonic" energy loss process leads to progressive equilibrium in the medium***

⇨ ***Fix the partonic EoS, the bulk properties***

Direct reconstruction of D^0

STAR Preliminary

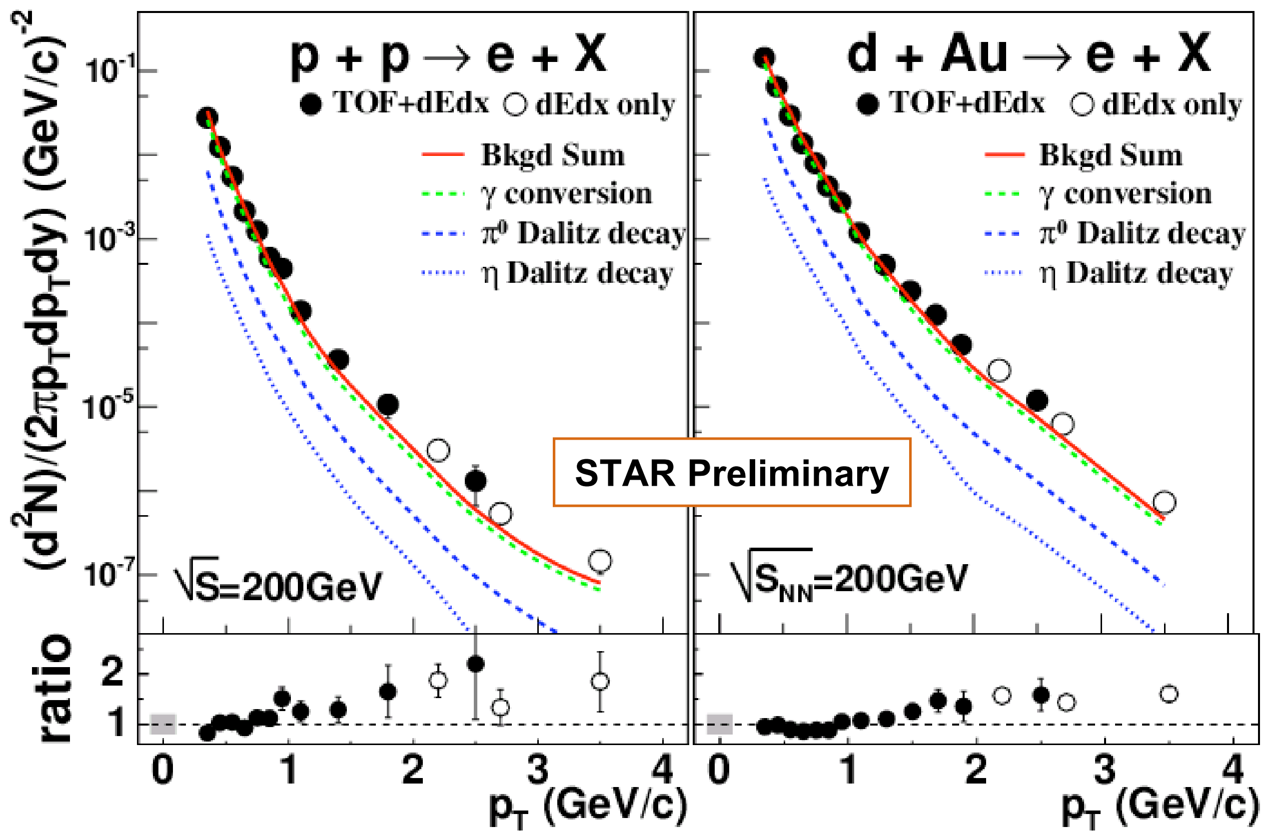
$$D^0 \rightarrow K^- + \pi^+ (\mathrm{Br}.3.83\%)$$



First Direct Open Charm Reconstruction at RHIC

Event mixing method:
C. Adler et al., *Phys. Rev.* ***C66***, *061901(R)(2002)*
H. Zhang, *J. Phys.* ***G30***, *S577(2004)*

Electron spectra from D decay



An increasing excess found at higher p_T region, p_T > 1.0 GeV/c,
→Expected contribution of semi-leptonic decays from heavy flavor hadrons

STAR: ***nucl-ex/0407006***

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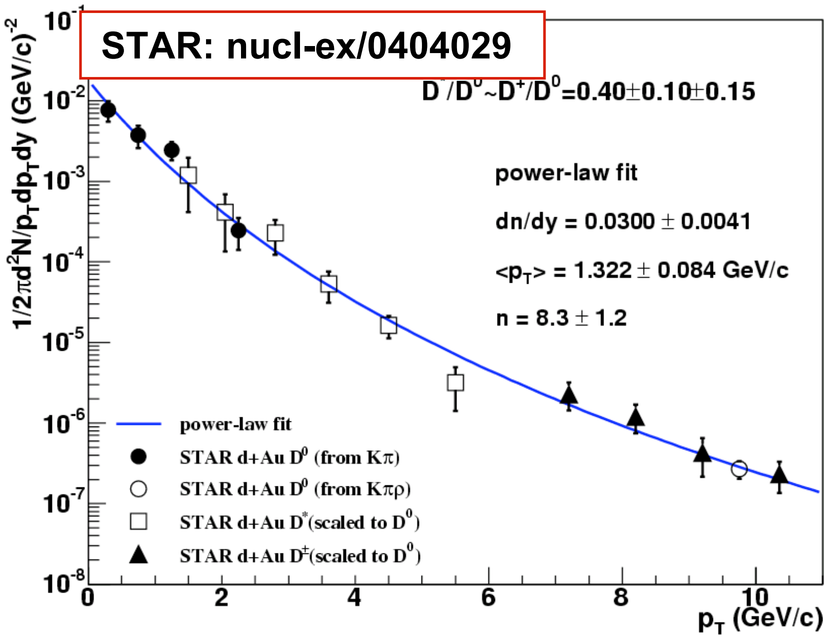
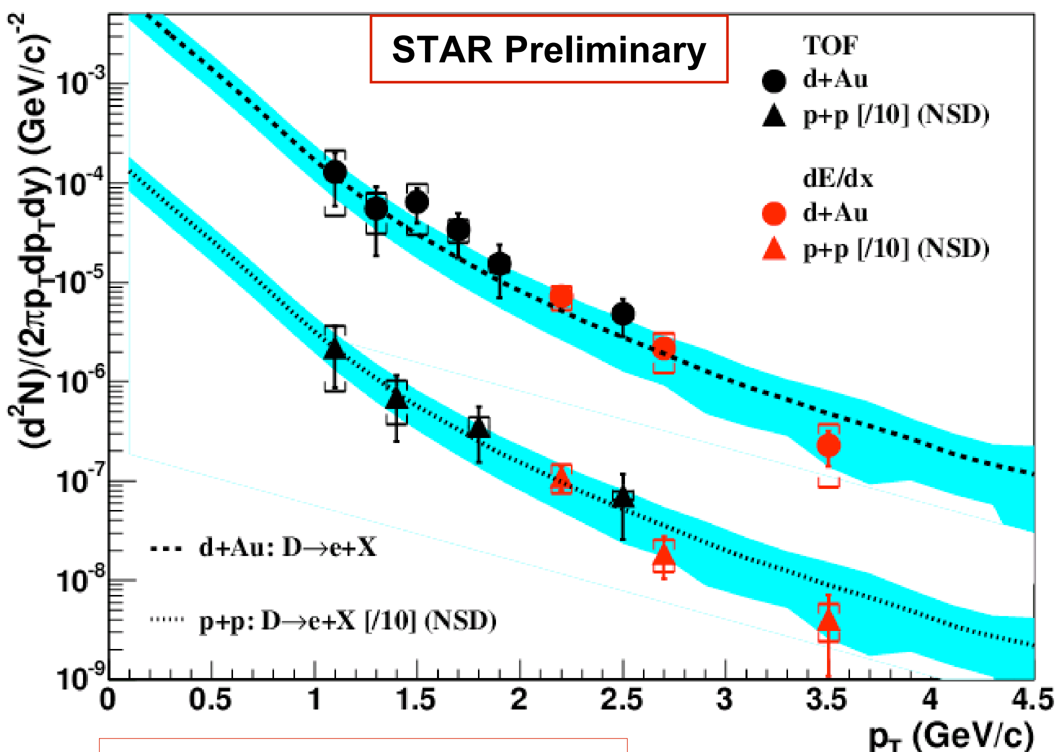
Consistent in D measurements



Directly reconstructed D mesons



Electrons from D decay

D and electron spectra are consistent!

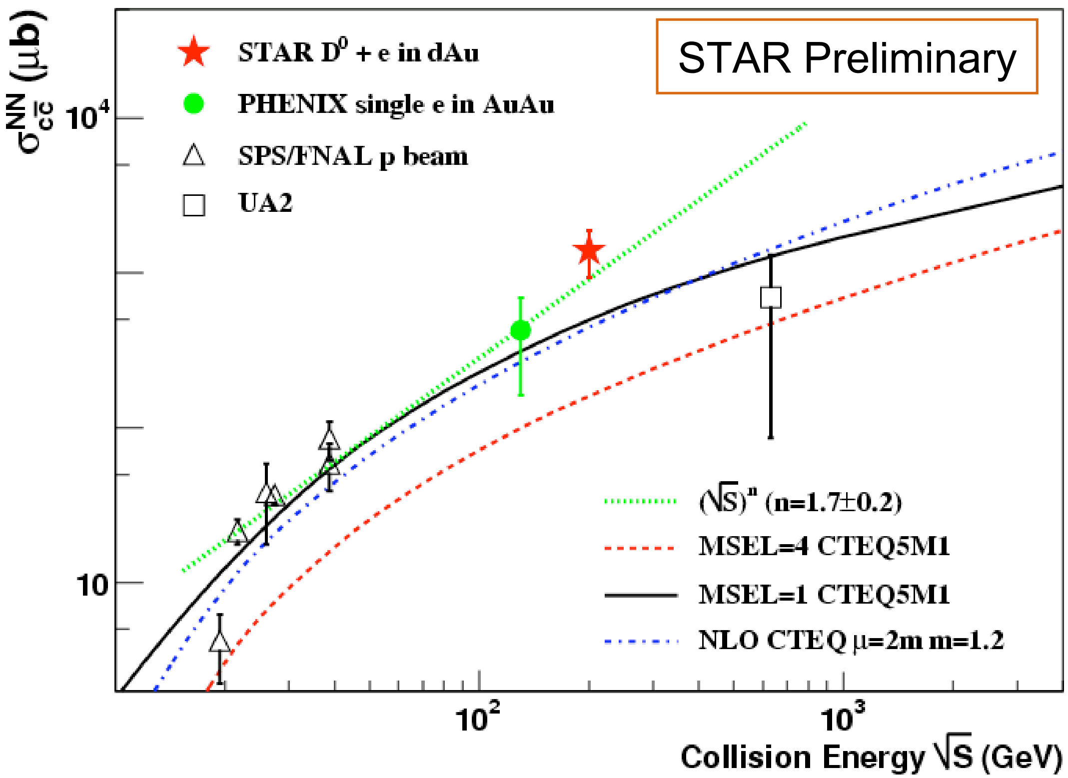
Charm production cross-section

//Talk/2004/11MIT/nxu_mit_26oct04//

1) NLO pQCD calculations under-predict the ccbar production cross section at RHIC

2) Power law for ccbar production cross section from SPS to RHIC:
n ~ 2
(n~0.5 for charged hadrons)

3) Large uncertainties in total cross section due to rapidity width, model dependent(?).



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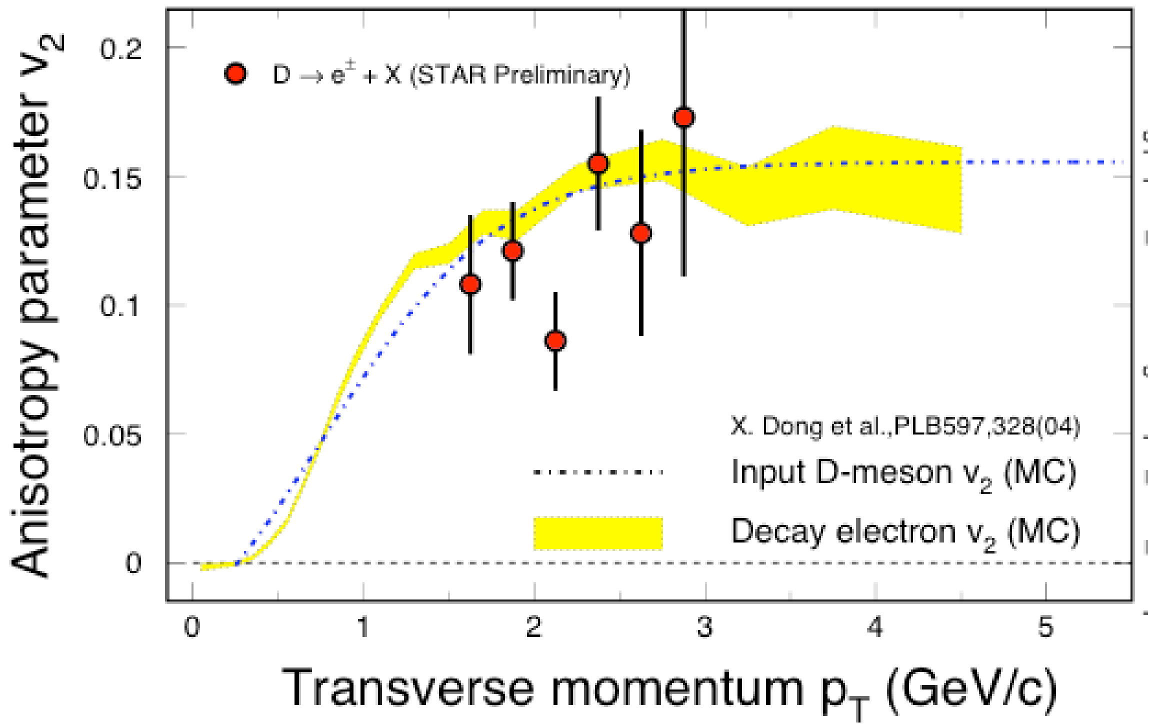
Open charm v_2 - a comparison



1) *Constituent Quark Scaling for open charm hadron production?*
2) *Flow of charm-quark and the thermalization among light flavors?*
3) *…????*

Preliminary Data: F. Laue, SQM04
MC: X. Dong, S. Esumi, P. Sorensen, N. Xu and Z. Xu, Phys. Lett. ***B597****, 328(2004).*

Charm production

1) Open charm yields measured in both 200GeV p+p and d+Au collisions. No evidence of deviation from binary collision scaling in d+Au collisions

$$\sigma_{c\bar{c}}^{total} = 700 \sim 1200 (\mu b)$$

2) Preliminary results of electron v_2 - consistent with MC. More background study underway.

3) Perturbative calculations under predicted both yields and spectrum shape. Hadronization process not under control

4) Study open charm v_2 and J/ψ yields to address thermalization issues at RHIC.

Pressure, Flow, …

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$$\tau ds = dU + pdV$$

s – entropy; p – pressure; U – energy; V – volume

$\tau = k_B T$, thermal energy per dof

In high-energy nuclear collisions, *interaction* among *constituents* and *density distribution* will lead to:

pressure gradient ⇒ collective flow

- ⇒ number of degrees of freedom (dof)
- ⇒ Equation of State (EOS)
- ⇒ No thermalization needed – pressure gradient only depends on the ***density gradient and interactions***.
- ⇒ Space-time-momentum correlations!

Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_t dp_t dy}\left[1 + \sum_{i=1} 2 v_i \cos(i\phi)\right]$$

$$p_t = \sqrt{p_x^2 + p_y^2}, \qquad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass:

- Directed flow (v_1) – early
- Elliptic flow (v_2) – early
- Radial flow – integrated over whole evolution

Note on collectivity:

1) Effect of collectivity is accumulative – final effect is the sum of all processes.
2) Thermalization is not needed to develop collectivity - pressure gradient depends on ***density gradient*** and ***interactions***.

Hadron Spectra From RHIC

mid-rapidity, p+p and Au+Au collisions at 200 GeV

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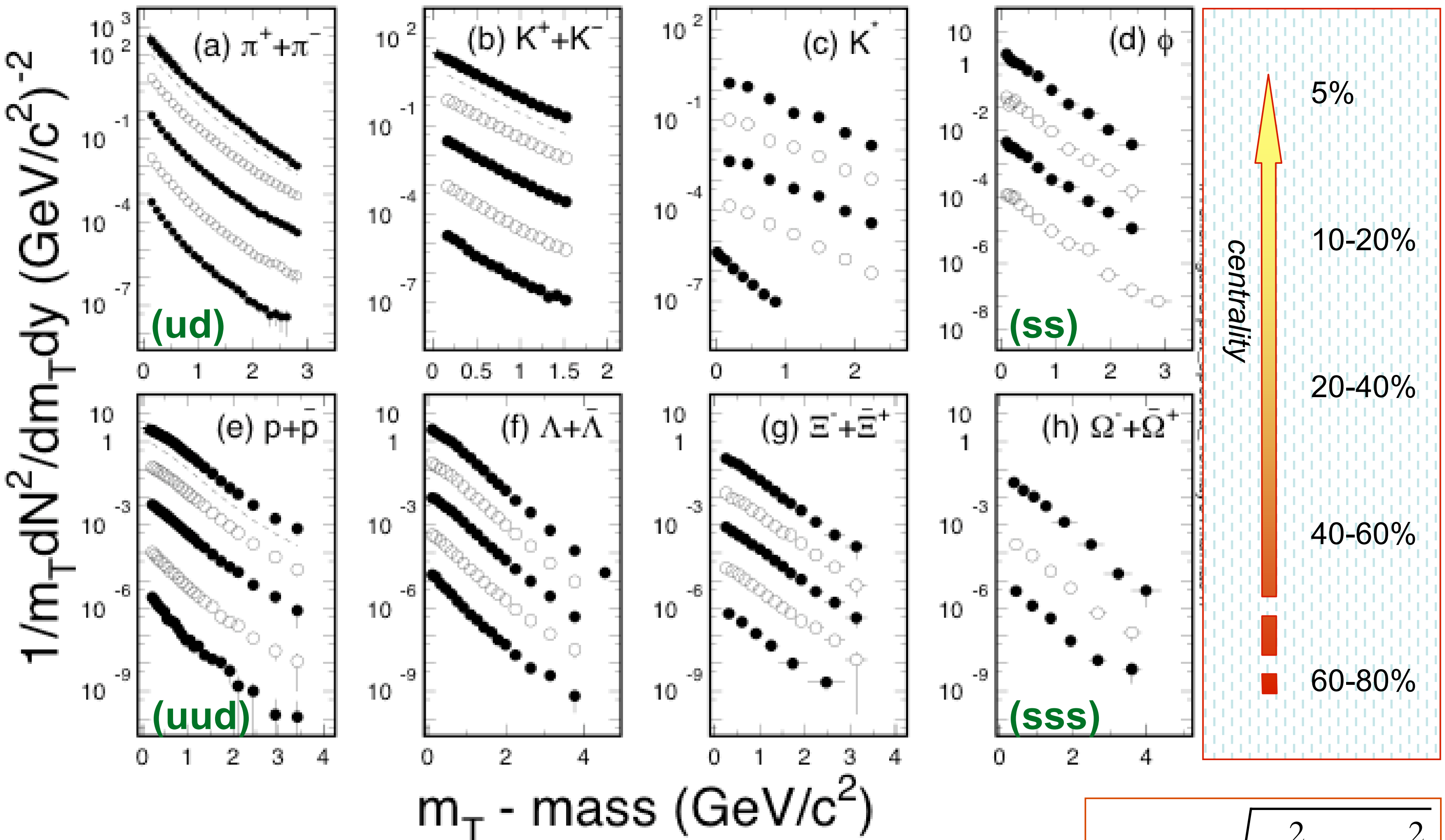

$$m_T = \sqrt{p_T^2 + m^2}$$

Thermal fits: T_{fo} vs. < β_T >

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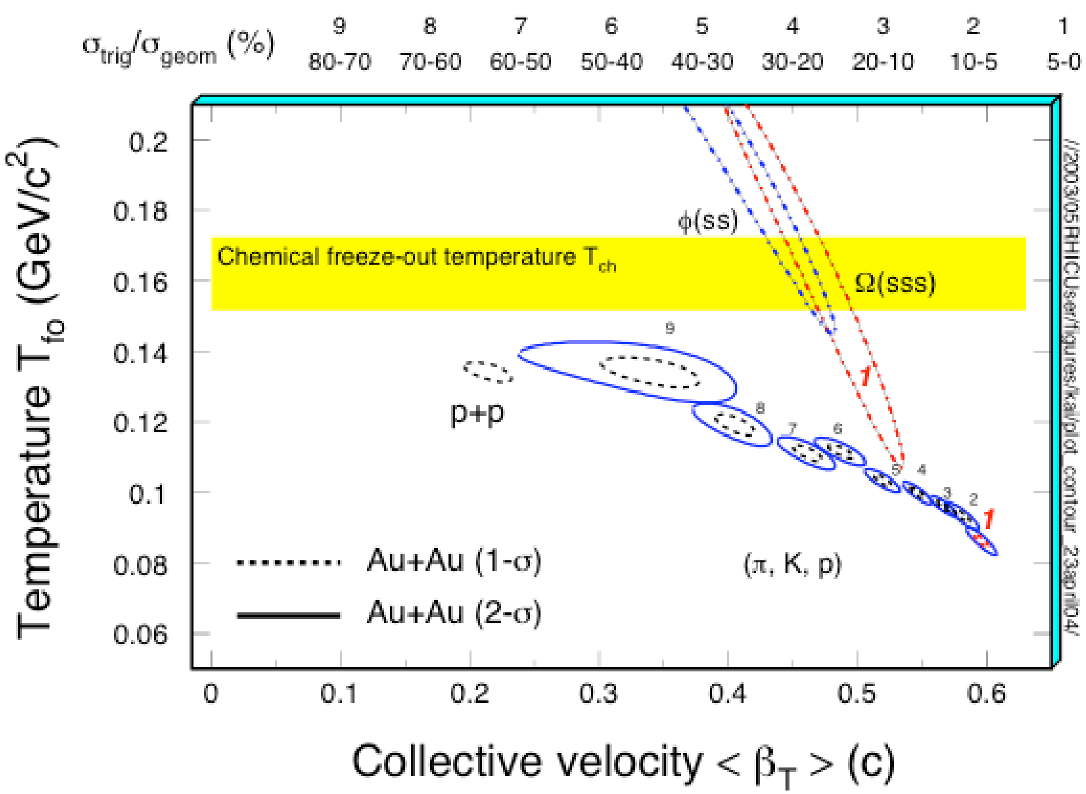
200GeV Au + Au collisions



1) π, *K*, and *p* change smoothly from peripheral to central collisions.

2) At the most central collisions, <β_T> reaches 0.6c.

3) Multi-strange particles φ, Ω are found at higher T_{fo} ($T \sim T_{ch}$) and lower <β_T>

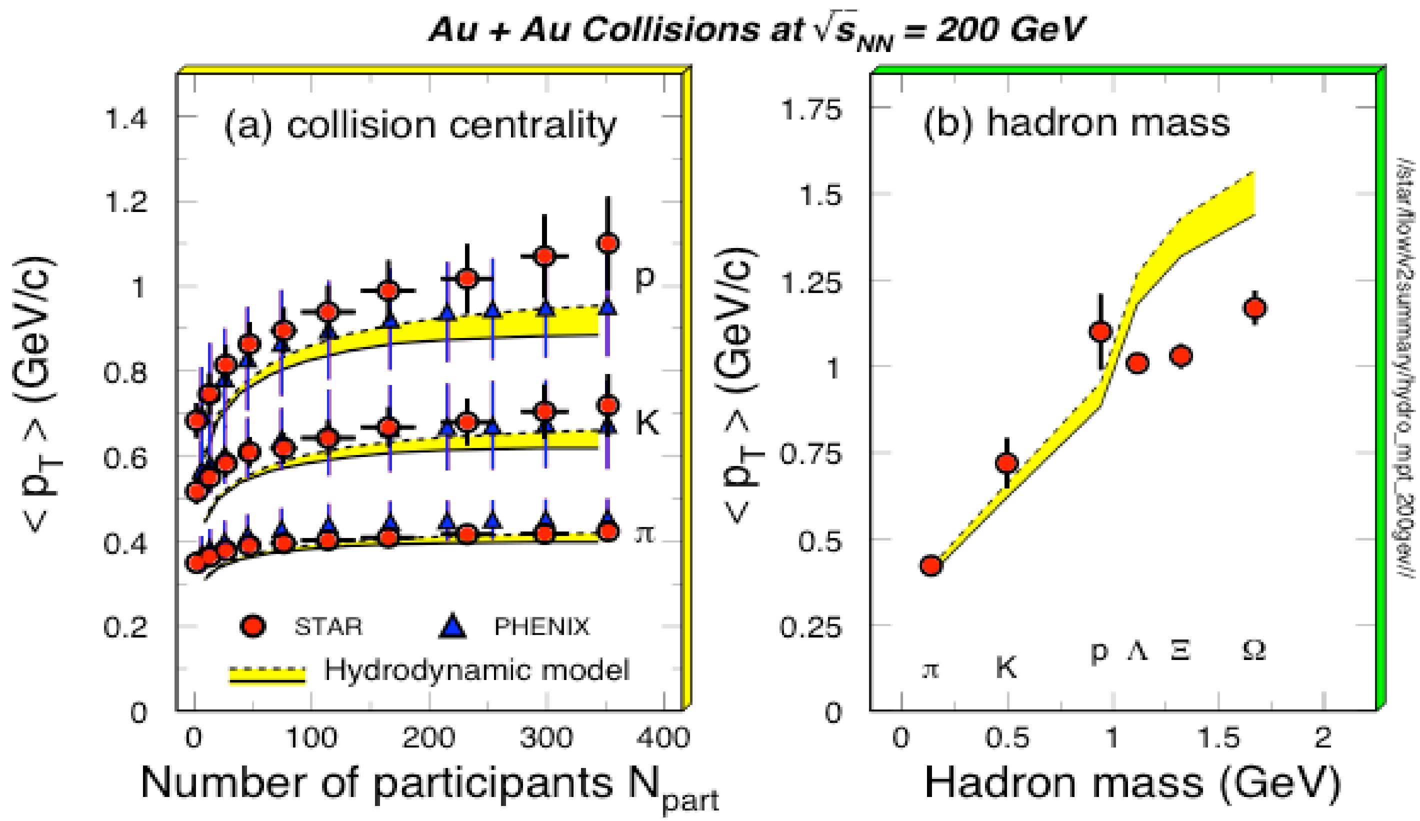
➪ **Sensitive to early partonic stage!**

➪ **How about v_2?**

STAR: NP**A715**, 458c(03); *PRL* ***92***, *112301(04);* ***92****, 182301(04).*

Chemical Freeze-out: inelastic interactions stop
Kinetic Freeze-out: elastic interactions stop

Compare with Model Results

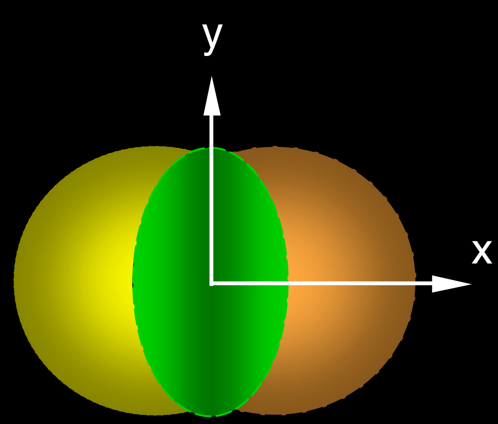


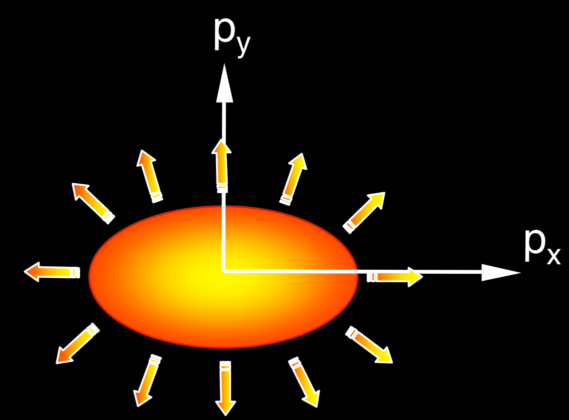
Model results fit to *π, K, p* spectra well, but over predicted $<p_T>$ for multi-strange hadrons - **Do they freeze-out earlier?**

Phys. Rev. ***C69*** *034909 (04); Phys. Rev. Lett.* ***92****, 112301(04);* ***92****, 182301(04); P. Kolb et al., Phys. Rev.* ***C67*** *044903(03)*

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇒ momentum-space-anisotropy

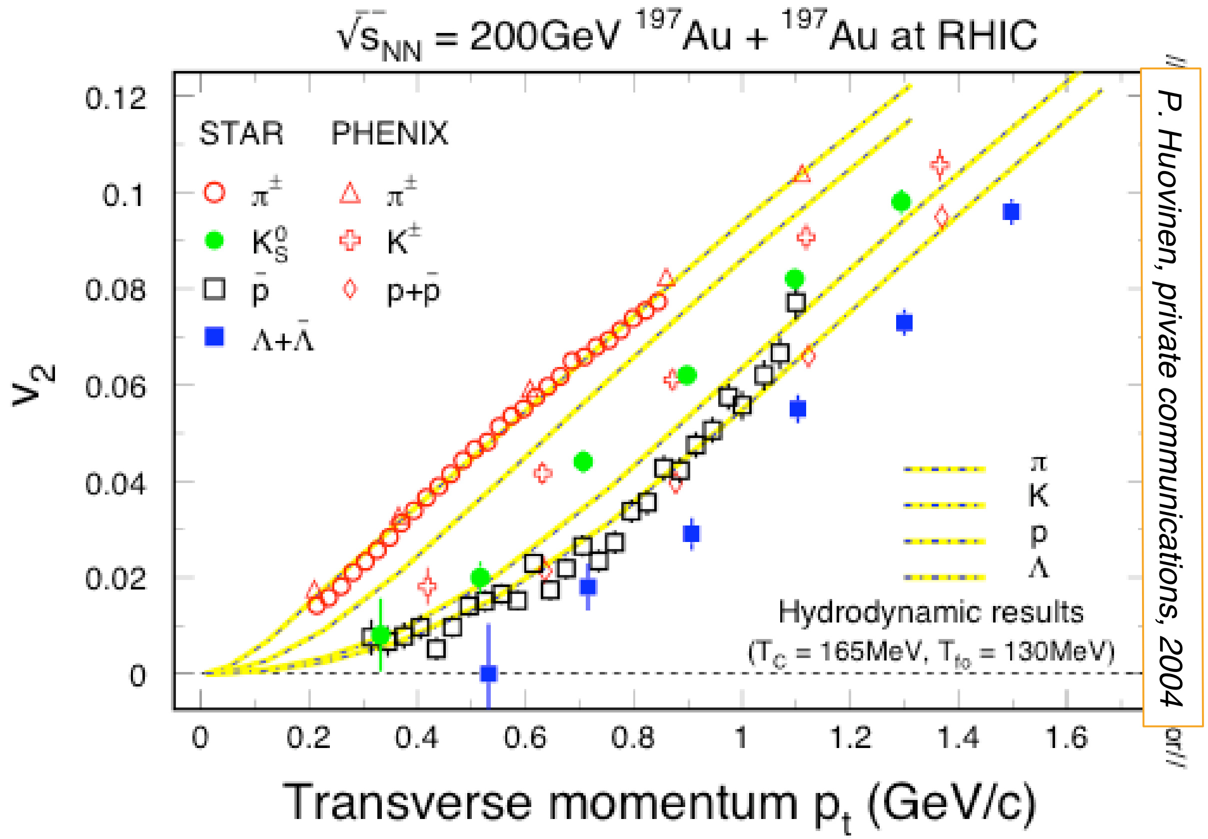




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

v_2 at low p_T region



- At low p_T, hydrodynamic model seem to fit for minimum bias events, especially the mass hierarchy.
- More theory work needed to understand details such as v_2 centrality dependence, consistency with hadron spectra.

v_2 at all p_T measured region

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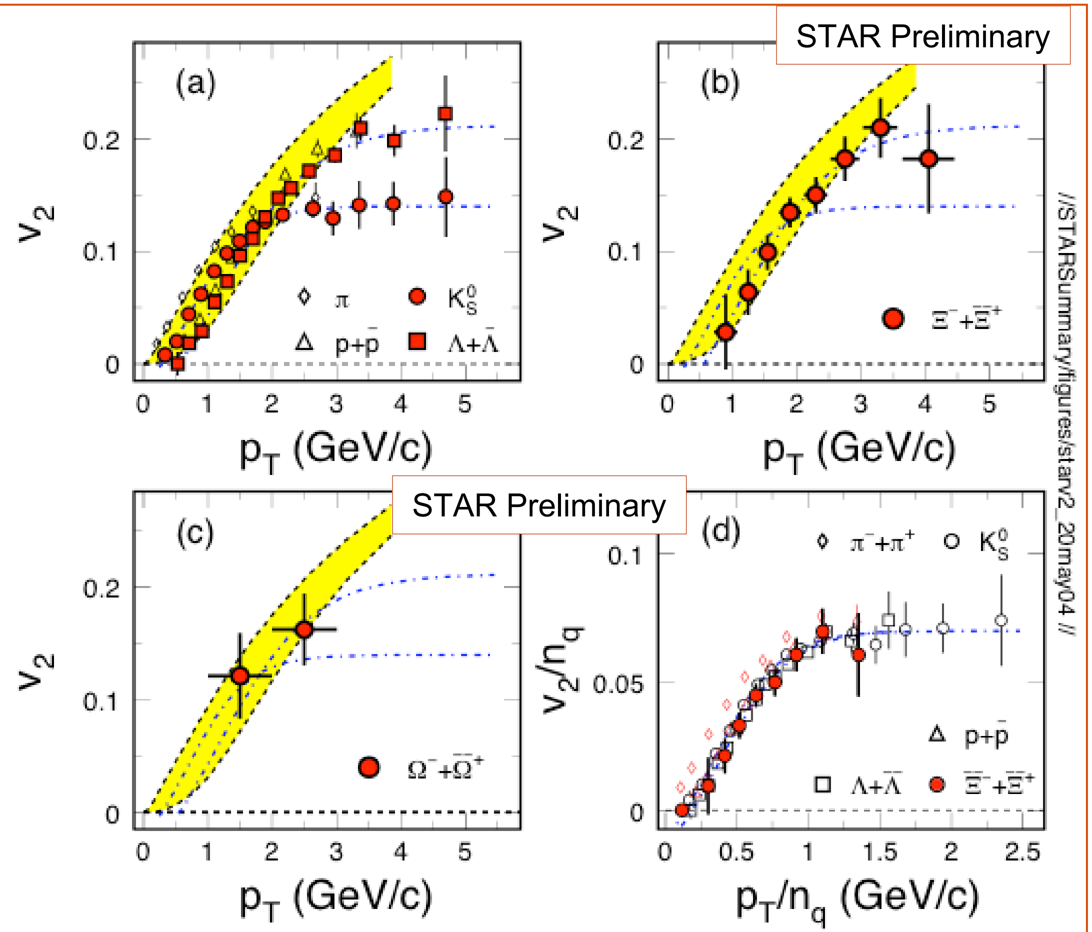

PHENIX: PRL91, 182301(03) *STAR: PRL92, 052302(04)*
*Models: R. Fries et al, PR**C68**, 044902(03), Hwa, nucl-th/0406072*

The v_2, the spectra of multi-strange hadrons, and the scaling of the number of constituent quarks

➪ **Partonic collectivity has been attained at RHIC!**

➪ **Deconfinement, model dependently, has been attained at RHIC!**

Next question is the thermalization of light flavors at RHIC:

- v_2 of charm hadrons

- J/□ distributions !!

Nuclear Modification Factor

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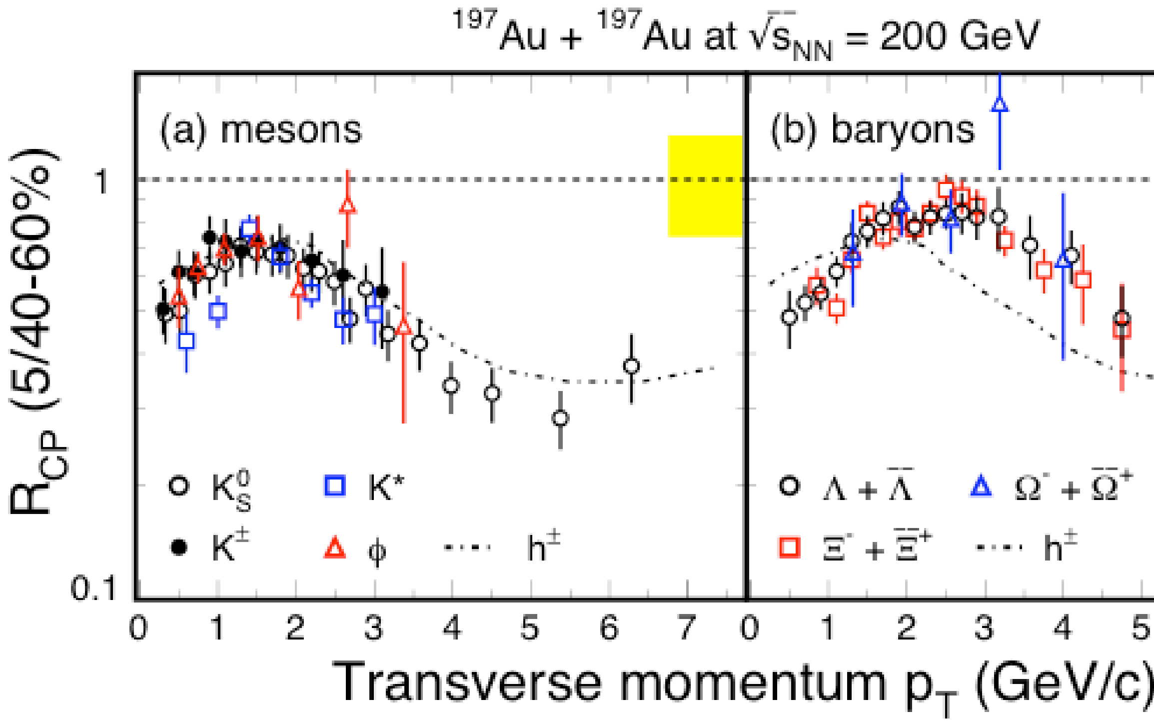


$$R_{CP}(p_T) = \frac{d^2N^{central} / (N^{central}_{binary} dp_T dy)}{d^2N^{peripheral} / (N^{peripheral}_{binary} dp_T dy)}$$

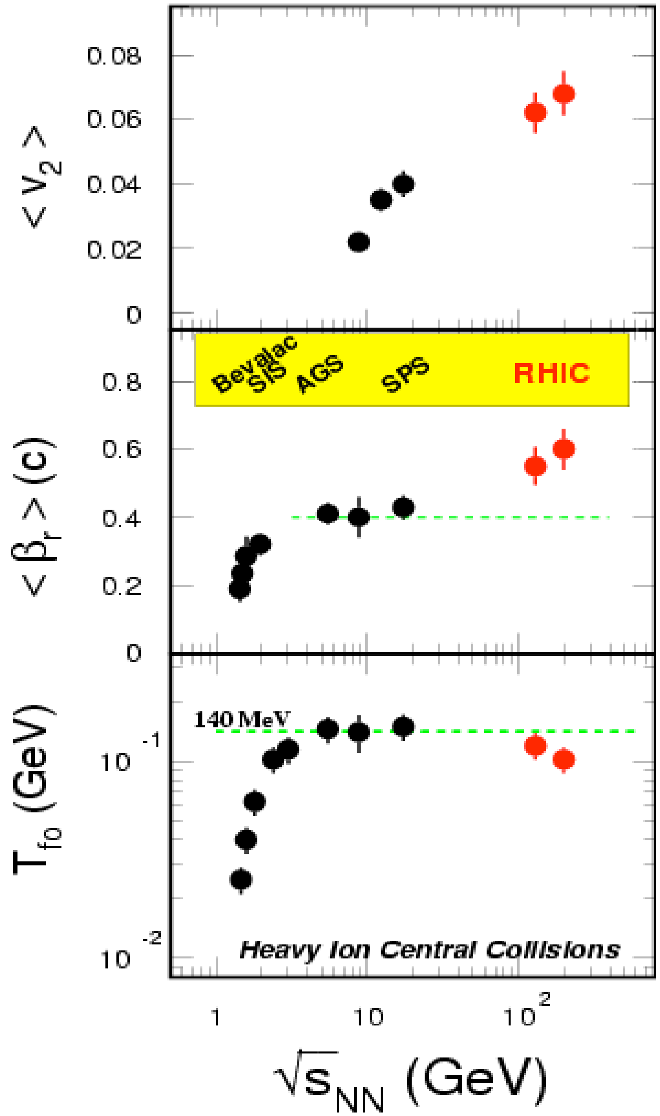
1) Baryon vs. meson effect!

2) Hadronization via coalescence

3) Parton thermalization (model)

- (K^0, Λ): *PRL* ***92****, 052303(04); NP* ***A715****, 466c(03);*
- *R. Fries et al, PR****C68****, 044902(03)*

Bulk Freeze-out Systematics



The additional increase in β_T is likely due to partonic pressure at RHIC.

1) v_2 self-quenching, hydrodynamic model works at low p_T
2) Multi-strange hadron freeze-out earlier, $T_{fo} \sim T_{ch}$
3) Multi-strange hadron show strong v_2

Partonic Collectivity at RHIC

1) Copiously produced hadrons (*□, K, p, □*) freeze-out:
T_{fo} = 100 MeV, $□_T$ = 0.6 (c) > $□_T$(SPS)

2)* Multi-strange hadrons freeze-out:
T_{fo} = 160-170 MeV (~ T_{ch}), $□_T$ = 0.4 (c)

3)** Multi-strange v_2:
Multi-strange hadrons □ and □ flow!

4)*** Constituent Quark scaling:
Seems to work for v_2 and R_{AA} (R_{CP})

Partonic (*u,d,s*) collectivity at RHIC!

Summary & Outlook

(1) Charged multiplicity - high initial density

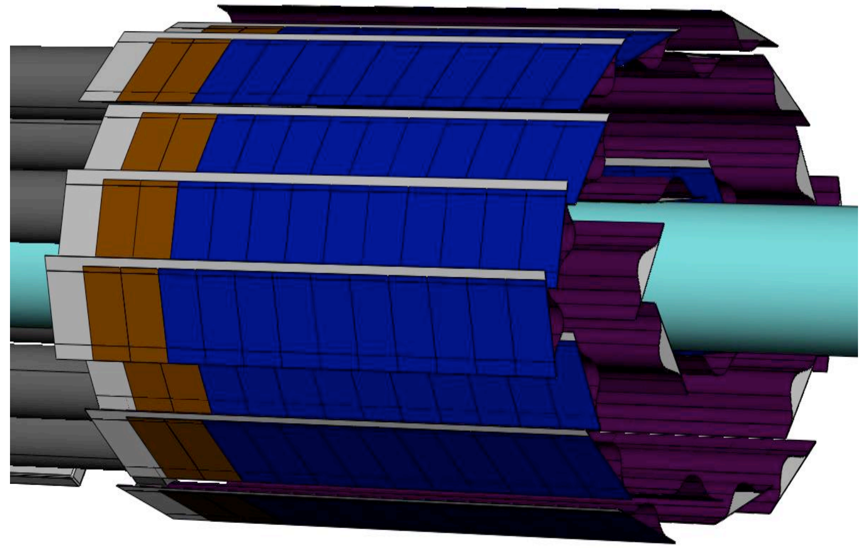
(2) Parton energy loss - ***QCD*** at work

(3) Collectivity - pressure gradient ∂P_{QCD}

⇨ **Deconfinement and Partonic collectivity**

Open issues - partonic (***u,d,s***) thermalization
- heavy flavor v_2 and spectra
- di-lepton and thermal photon spectra

Upgrades at STAR



STAR MRPC - TOF

STAR MicroVertex Tracker

Active pixel sensors (APS)
Two layers of thin silicon

- **Full open charm measurements**
- **Full resonance measurements with both hadron and lepton decays**

Open Issues

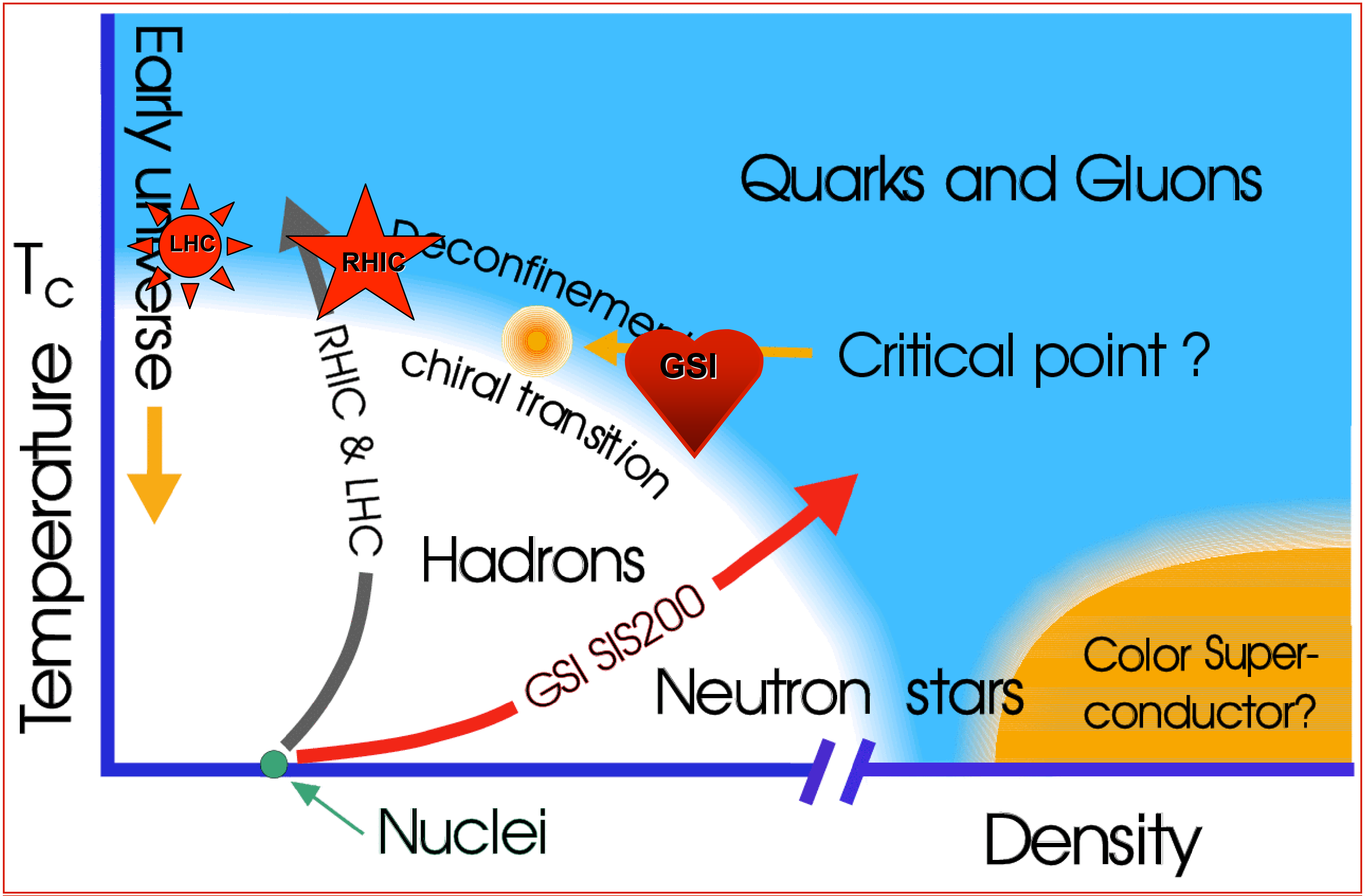
1) **Nuclear stopping/baryon transport:**
   - topological junction, a la Gyulassy, *nucl-th/0407095*
   - nucleon structure function, a la Muller, *PRL**91**, 052302(03)*

2) **Thermalization and QGP temperature:**

3) **Hadronization via coalescence/recombination:**
   - p+p collisions?
   - low p_T pions? Where are gluons? Heavy flavor?

4) **Chiral symmetry restoration:**

Details for QGP discovery!


Early universe
LHC
RHIC
Deconfinement
Quarks and Gluons
Critical point ?
GSI
chiral transition
RHIC & LHC
Temperature
T_c
Hadrons
GSI SIS200
Neutron stars
Color Super-
conductor?
Nuclei
Density